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Original article

Soils development in opencast coal mine spoils reclaimed for 1–13 years in the West-Northern Loess Plateau of China

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A B S T R A C T

Soil development is the key process of mine spoil reclamation. To investigate the effects of different plant species and reclamation time on the soil development, 9 plots in the reclaimed spoils of Pingshuo opencast coal mine in Shanxi, China were established and the physical, chemical and microbiological properties of the soils were analyzed. The results showed that, soil bulk density and field capacity in plots with longer reclamation time were statistically different from plots with younger vegetation in both the 0–20 cm and 20–40 cm soil layers. Accordingly, values of organic matter and available nitrogen levels showed a significant increase in both 0–20 cm and 20–40 cm depth with reclamation time increasing and the top layer marked higher value except for some individual data. The organic matter in plot 8 in 0–20 cm depth with 13-year old vegetation reached 9.45 g kg^{-1}, about 2.5-, 2.0- and 3.1-fold higher than the plots of 1-, 3- and 4-year old vegetation respectively. Total microbial amount showed a positive correlation with contents of organic matter which reached 1436.72 × 105 g^{-1} in plot 8 with 13-years old vegetation, about 11.3-fold greater than plot 1 of 1-yr old vegetation. Plots planted with sea buckthorn (*Hippophae rhamnoides* ssp. *sinensis*) singly or mixed with other species tend to develop better soil aggregation and microbiological properties than other plots, which may be due to its particular biological characteristics, developed root system and high growth rate in the first 4–6 year and 8–10 year, indicating that sea buckthorn may be a good species choice for activating soil development in the early stage of reclamation.

1. Introduction

Mining activities have contributed greatly to China's economic development. At the same time, however, they have brought great damage to the eco-environment [1–3]. In China, about 2.88 Mha of land has been destroyed by mining [4], and the figure is increasing at an alarming rate of 46,700 ha per year [5]. In general, opencast mining degrades 2–11 times more land than underground mining [3]. Opencast mining excavations (1) eliminate vegetation; (2) changes topography permanently; (3) alters soil and subsurface geological structure permanently and drastically, and (4) disrupts surface and subsurface hydrologic regimes [6]. The process transforms fertile cultivated land into wasteland and causes serious environmental pollution and ecological degradation, which can lead to the loss of biodiversity, amenity, and economic wealth [1,7]. Adverse properties of spoil material, such as lack of organic matter, sensitivity to erosion, toxicity, unsuitable water regime and nutrient deficiency, commonly reduces bio-productivity in post-mining landscapes [8]. However, these effects can be mitigated by ecological restoration and reclamation [9].

The establishment of a plant cover on mine spoils is only part of the revegetation objective. The main aim of any restoration process is to create sustainable plant communities representative of the composition and diversity of the surrounding natural plant communities [10,11]. Successful revegetation is dependent on many factors, but one of the most important issues for the restoration of functional ecosystems in post-mining lands is soil formation because most sites have unfavorable soil physical and chemical properties [1,5]. Soil properties, identified as indicators of soil quality, include soil organic matter, total organic nitrogen, total organic carbon, nutrient availability, pH, and electrical conductivity, etc. [11]. However, most critical is the accumulation of organic matter in the surface layers of the spoil material because this results

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in positive changes in physical and chemical soil properties, such as water holding and sorption capacities, nutrient content and availability, soil bulk density, buffering capacity, etc. Moreover, such organic matter is an energy source for the soil biota, which drives decomposition and mineralization of plant residues, thereby releasing nutrients. Soil formation and organic matter accumulation in post-mining lands depends on the development of vegetation cover and litter productivity [8].

Many spoil characteristics limit soil and plant productivity [12]. Reforestation is often used for the reclamation of disturbed coal mine lands because trees are efficient bioaccumulators that can add much organic material to the soil, both above and below ground, and are associated with a relatively large number and diversity of soil organisms. Trees create easily new self-sustaining top soils in and above the forested mine spoils. However, not all trees are equally effective soil generators [13]. So, selecting an appropriate species is very important for ensuring a self-sustainable vegetation cover [1,14]. The capacity of different plant species to modify mine spoil characteristics, at different ecosystem development stages during the years after reclamation, has been found to differ considerably [15]. However, most studies of revegetation have focused on techniques for vegetation establishment, while little attention has been paid to the processes of soil development and natural recruitment [16].

The aim of this study was to describe and evaluate the effects of different plant species and time after reclamation on soil properties development, taking the reclaimed spoils of Pingshuo opencast coal mine in Shanxi, China as a case study.

2. Materials and methods

2.1. Study site

This study was conducted on reclaimed mine spoils in the largest opencast coal mining area in China - Pingshuo, which includes 3 mines: AnTaibao, Anjialing and East opencast mines (Fig. 1). The Pingshuo opencast mine area is located on the borders of Shanxi Province, Shaanxi and Inner Mongolia in the east of the Loess Plateau, west-north of China, with geographical coordinates: 112°11′–112°30′ E, 39°23′–39°37′ N. This is an ecologically fragile area with an arid to semi-arid continental monsoon climate (Fig. 1). The altitude is 1300–1400 m and the terrain is loess hills with grass vegetation. The average annual rainfall is about 450 mm, with 65% falling from June to September. The average annual evaporation, however, is about 2160 mm, 4.6 times more than the rainfall. The average annual temperature is 6.2 °C and the average wind speed is 2.3–4.7 m s^{-1} with maximal value 20 m s^{-1}. Formerly, this region was a mainly forest and prairie landscape, but during the last 200 years, the primary vegetation has been damaged which leading to chronic problems of erosion. Its chestnut soils are characterized by low levels of organic matter and poor structure. The common water and wind erosion modulus of the soils are 10000 t km^{-2} a^{-1} and 2000 t km^{-2} a^{-1}, respectively [5].

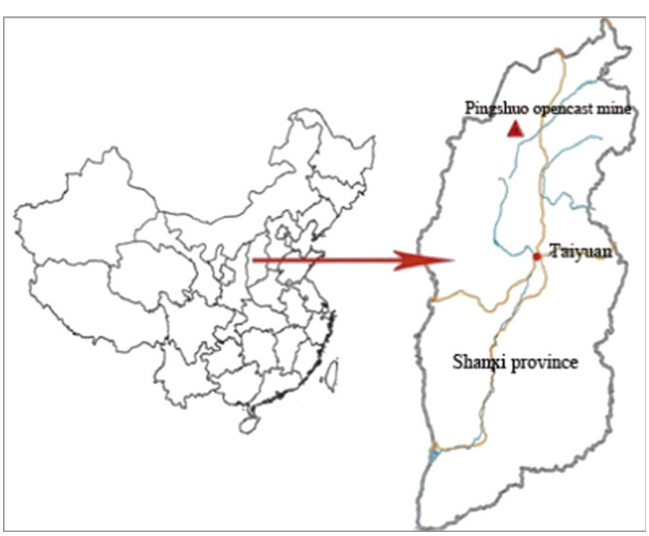

Fig. 1. A sketch map showing geographical location of Pingshuo opencast coal mine.

The extensive mining activity caused the fragile eco-environmental situation worse in this area. The original landform, geological strata and ecosystem no longer exist. Bai et al. [17–19] have been conducted research on ecosystem reconstruction in these destroyed lands since the mid-1980s, including dumping design, surface soil covering, erosion control, plant species selection and configuration, fertilizing and tending management etc., and several self-sustaining vegetations have been established.

2.2. Sample plots

9 sample plots were established in the reclaimed spoils differ in plant species and time of reclamation in September 2006. The area of each plot is 1 ha m^2 (100 × 100 m). The characteristics of their vegetation, soil texture and time since reclamation are listed in Table 1.

2.3. Soil sampling and analysis

Soil samples for physical and chemical parameters measurement except for soil aggregation were taken from 2 depths (0–20 and 20–40 cm) into the soil/spoil profile. All samples were collected in October 2006. Six sub-plots of 5 × 5 m were established at random locations in every plot, and five sampling points were selected in each sub-plot. In each sub-plot, the five individual soil samples collected from the corresponding layers were mixed in the same weight ratio with each sample at size of 2.5 kg.

Soil physical parameters were measured following the methods of the Soil Physics Laboratory at the Soil Research Institute of Chinese Academy of Sciences in Nanjing [20]. Thus, the Bulk density (BD) of the soil samples was measured with stainless Kopecky cylinders, then the samples were oven-dried at 105 °C for 48 h, and

Table 1
Characteristics of sample plots.

Sample number	Reclamation time (years)	Vegetation	Soil texture
1	1	Standing Milk-vetch (*Astragalus adsurgens*)	Light loam
2	3	Sea-buckthorn (*Hippophae rhamnoides* ssp. *sinensis*) × locust (*Robinia pseudoacacia*) × korshinsk peashrub (*Caragana korshinskii*)	Light loam
3	4	Alfalfa (*Medicago sativa*) × standing Milk-vetch	Light loam
4	5	Sea-buckthorn	Light loam
5	7	Sea-buckthorn × narrow-leaved oleaster (*Elaeagnus angustifolia*) × river locust (*Amorpha fruticosa*)	Sandy loam
6	7	Narrow-leaved oleaster × locust × korshinsk peashrub	Sandy loam
7	10	Sea-buckthorn	Sandy loam
8	13	Locust × Chinese pine (*Pinus tabulaeformis*) × Elm (*Ulmus pumila*)	Light loam
9	13	Locust × korshinsk peashrub	Light loam